1.4 Overview of physiological parameters: temperature, blood pressure, heart rate, oxygen saturation, respiration, glucose

Vital sign measurements are a crucial aspect of physiotherapy assessment, screening for potential red flags and to guide treatment. These measurements are termed "vital" as their measurement and assessment is the critical first step for any clinical evaluation. Vital signs are indicators of a persons health condition and normal measurements provide assurance of proper circulatory, respiratory, neural, and endocrinal functions. Furthermore, they are commonly used to universally communicate a patient's condition and severity of the disease

Vital signs consist of:

1. Temperature
2. Pulse rate
3. Blood pressure
4. Respiratory rate.
5. Blood oxygen saturation via pulse oximetry
   Vital signs can be influenced by a number of factors. It can vary based on age, time, gender, medication, or a result of the environment.

- Healthcare providers must understand the various physiologic and pathologic processes affecting these sets of measurements and their proper interpretation.

Vital signs play an important role in emergency departments (ED) and on the wards, to determine patients at risk of deterioration.

- The degree of vital sign abnormalities may also predict the long-term patient health outcomes, return emergency room visits, and frequency of readmission to hospitals, and utilization of healthcare resources.
- Vital signs help to predict physical therapy indications, contraindications, and outcomes.
- Vital signs are appropriate to characterize or quantify cardiovascular and pulmonary signs and symptoms as part of an assessment of aerobic capacity and endurance.

Components

Body Temperature

The normal body temperature for a healthy adult is approximately 98.6 degrees Fahrenheit/37.0 degrees centigrade. The human body temperature typically ranges from 36.5 to 37.5 degrees centigrade (97.7 to 99.5 degrees Fahrenheit).Health care providers use the axillary, rectal, oral, and tympanic membrane most commonly used to record body temperature, and the electronic and infrared thermometers are the devices most commonly used.

Sites for measurement of body temperature

Oral temperature: It is the most commonly used method, is considered very convenient and reliable. Here we place the thermometer under the tongue and close the lips around it. The posterior sublingual pocket is the area that gives the highest reliability.

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1. Tympanic temperature: In this method, the thermometer is inserted into the ear canal. This site is convenient but less accurate and hence not recommended.
2. Axillary temperature: In this, we place the thermometer in the axilla while adducting the arm of the patient. This site is convenient but generally considered less accurate and hence not recommended.
3. Rectal temperature: The thermometer is inserted through the anus into the rectum after applying a lubricant. This method is very inconvenient, but since it measures the internal measurement, it is very reliable. It is usually considered the "gold standard" method of recording temperature.
4. Skin temperature: Digital thermometer can be used to measure the quick temperature from the skin of the forehead. It has been widely used now in this COVID-19 pandemic to avoid cross-contamination as the thermometer is kept 3-5cm away from the patient's forehead.

Body temperature is affected by many sources of internal and external variables. Besides the site of measurement, the time of day is an essential factor leading to variability in the temperature record, secondary to the circadian rhythm. Other factors influencing body temperature are gender, recent activity, a person's relative physical fitness, food, and fluid consumption, and, in women, the stage of the menstrual cycle.

Pulse Rate

Pulse rate is defined as the wave of blood in the artery created by contraction of the left ventricle during a cardiac cycle. The most common sites of measuring the peripheral pulses are the radial pulse, ulnar pulse, brachial pulse in the upper extremity, and the posterior tibialis or the dorsalis pedis pulse as well as the femoral pulse in the lower extremity. Clinicians also measure the carotid pulse in the neck. In day to day practice, the radial pulse is the most frequently used site for checking the peripheral pulse, where the pulse is palpated on the radial aspect of the forearm, just proximal to the wrist joint.

Parameters for assessment of pulse

1. Rate: The normal range used in an adult is between 60 to 100 beats /minute with rates above 100 beats/minute and rates and below 60 beats per minute, referred to as tachycardia and bradycardia, respectively. Changes in the rate of the pulse, along with changes in respiration is called sinus arrhythmia. In sinus arrhythmia, the pulse rate becomes faster during inspiration and slows down during expiration.
2. Rythym: Assessing whether the rhythm of the pulse is regular or irregular is essential. The pulse could be regular, irregular, or irregularly irregular. Irregularly irregular pattern is more commonly indicative of processes like atrial flutter or atrial fibrillation.
3. Volume: Assessing the volume of the pulse is equally essential. A low volume pulse could be indicative of inadequate tissue perfusion; this can be a crucial indicator of indirect prediction of the systolic blood pressure of the patient.
4. Symmetry: Checking for symmetry of the pulses is important as asymmetrical pulses could be seen in conditions like aortic dissection, aortic coarctation, Takayasu arteritis, and subclavian steal syndrome.
5. Amplitude and rate of increase: Low amplitude and low rate of increase could be seen in conditions like aortic stenosis, besides weak perfusion states. High amplitude and rapid rise can be indicative of conditions like aortic regurgitation, mitral regurgitation, and hypertrophic cardiomyopathy.

Respiratory Rate

The respiratory rate/the number of breaths per minute is defined as the one breath to each movement of air in and out of the lungs. The normal breathing rate is about 12 to 20 beats per minute in an average adult. In the pediatric age group, it is defined by the particular age group.

Parameters that need to be included are its rate, depth of breathing, and its pattern rate of breathing.

1. Rates: Rates higher or lower than expected are termed as tachypnea and bradypnea, respectively. Tachypnea described as a respiratory rate more than 20 beats per minute could occur in physiological conditions like exercise, emotional changes, pregnancy, and pathological conditions like pain,

pneumonia, pulmonary embolism, asthma, etc. Bradypnea which is ventilation less than 12 breaths/minute can occur due to worsening of any underlying respiratory condition leading to respiratory failure or due to usage of central nervous system depressants like alcohol, narcotics, benzodiazepines, or metabolic derangements. Apnea is the complete cessation of airflow to the lungs for a total of 15 seconds which may appear in cardiopulmonary arrests, airway obstructions, the overdose of narcotics and benzodiazepines.

2. Depth of breathing: Hyperpnea is described as an increase in the depth of breathing. Hyperventilation, on the other hand, is described as both an increase in the rate and depth of breathing and hypoventilation describes the decreased rate and depth of ventilation. Depth of breathing involves what muscle groups they are using—for example, the sternocleidomastoid (accessory muscles) and abdominal muscles—the movement of the chest wall in terms of symmetry. The inability to speak in full sentences or increased effort to speak is an indicator of discomfort when breathing.
3. The pattern of breathing: There are many conditions which are based on the variation in the pattern of breathing. Biot's respiration is a condition where there are periods of increased rate and depth of breathing, followed by periods of no breathing or apnea. Cheyne-Stokes respiration is a peculiar pattern of breathing where there is an increase in the depth of ventilation followed by periods of no breathing or apnea. Kussmaul's breathing refers to the increased depth of ventilation, although the rate remains regular. Orthopnea refers to difficulty in respiration occurring on lying horizontal but gets better when the patient sits up or stands. Paradoxical ventilation refers to the inward movement of the abdominal or chest wall during inspiration, and outward movement during expiration, which is seen in cases of diaphragmatic paralysis, muscle fatigue, trauma to the chest wall.

Blood Pressure

Blood pressure is the force of circulating blood on the walls of the arteries, mainly in large arteries of the systemic circulation. Blood pressure is taken using two measurements: systolic (measured when the heartbeats, when blood pressure is at its highest) and diastolic (measured between heartbeats, when blood pressure is at its lowest). Blood pressure is written with the systolic blood pressure first, followed by the diastolic blood pressure.

The direct measurement of BP requires an intra-arterial assessment but it is not practical in clinical practice so BP is measured via non-invasive means. Earlier BP is measure with a stethoscope while watching a sphygmomanometer (i.e auscultation). However, semiautomated and automated devices that use the oscillometry method, which detects the amplitude of the BP oscillations on the arterial wall, have become widely used over the past 2 decades.

The brachial artery is the most common site for BP measurement.

Key Points for Accurately Measuring BP

All healthcare providers should be aware of making sure all the following pre-requisites are met before checking the blood pressure of the patient.

The patient should:

- Not have taken any caffeinated drink at least 1 hour before the testing and should not have smoked any nicotine products at least 15 minutes before checking the pressure. They
- Should have emptied their bladder should be before checking the blood pressure. Full bladder adds 10 mm Hg to the pressure readings.
- It is advisable to have the patient be seated for at least 5 minutes before checking his/her pressure. This step takes care of or at least minimizes the higher readings that could have occurred secondary to rushing in for the clinic appointment.
- The providers should not be having a conversation with the patient while checking his blood pressure. Talking or active listening adds ten mmHg to the pressure readings.
- The patient’s back and feet should be supported, and their legs should be uncrossed. Unsupported back and feet add six mmHg to the pressure readings. Crossed legs add 2 to 4 mmHg to the pressure readings.
- The arm should be supported at the heart level. Unsupported arm leads to 10 mmHg to the pressure readings. The patient’s blood pressure should get checked in each arm, and in younger patients, it should be tested in an upper and lower extremity to rule out the coarctation of the aorta.
- Cuff placement should be on a bare arm and not put over sweaters, coats, or other clothing. Using the correct cuff size is very important. Smaller cuff sizes give falsely high, and larger cuff sizes give a falsely lower blood pressure reading

Normative value

According to the 2017 ACC/AHA Guideline for the Prevention, Detection, Evaluation, and Management of High BP in Adults.[7]

BP Category	**SBP, mm Hg**		**DBP, mm Hg**
Normal	<120	and	<80
Elevated	120–129	and	<80
Hypertension			
Stage 1	130–139	or	80–89
Stage 2	≥140	or	≥90

Blood oxygen saturation

Oxygen saturation is considered as an essential element is the assessment and management of patient care. The term oxygen saturation refers to the percentage of oxygen circulating in an individuals blood. This is represented as arterial oxygen saturation (SaO2) which is measured using a non-invasive pulse oximetry (SpO2).

Normal values: 95-98%

Hypoxia: <92%

Electroencephalographic, visual and cognitive changes develop: <80-85%

Pulse oximetry has a specificity of 90% and sensitivity of 92% when detecting hypoxia. Most oximeters provide a reading 2% under or 2% over the results obtained by an arterial blood gas. For example, a 92% oxygen saturation on the pulse oximeter can actually be between 90 to 94%.

Factors that reduce the accuracy of a pulse oximetry reading include:

- Cold hands

- Wearing nail polish (especially blue, black or green)
- Wearing artificial nails
- Very low oxygen saturation levels (<80%)
- Skin thicker than normal
- Skin pigment (accuracy reduces with darker skin pigmentation
- Smoking (pulse oximeter can not tell the difference between the heightened carbon monoxide levels as a result of smoking and oxygen)

Factors that improve pulse oximeter signals

- Applying a topical vasodilator
- Warming up the skin
- Hand held below the level of the heart
- Different probe location (ear lobe)
- Different probe

1.5 Errors in Measurements

Errors in measurements refer to the discrepancies or deviations between the measured value and the true value of a quantity being measured. These errors can arise due to various factors and can impact the accuracy and reliability of measurement results. Understanding different types of errors is essential for improving the quality of measurements and obtaining more accurate data. Here are some common types of errors in measurements:

1. Gross Errors.
2. Systematic Errors. (*Instrumental Errors, Environmental Errors, Observational Errors.)*
3. Random Errors.
4. Limiting Errors or Guarantee Errors.
5. Relative (Fractional) Limiting Error

1. Gross Errors:

Gross errors are significant and noticeable mistakes that lead to inaccurate measurements. They can result from human errors, malfunctioning equipment, or procedural mistakes. Gross errors are often easy to identify due to their significant impact on the measurement result.

Example, (i) the experimenter may, due to an oversight, read the temperature as 31.5°C while the actual reading may be21.5°C.

(ii) He may transpose the reading while recording. For example, he may read 25.8°C and record 28.5°C instead.

2. Systematic Errors

These types of errors are divided into three categories :

(i). Instrumental Errors.

(ii). Environmental Errors.

(iii). Observational Errors.

(i). Instrumental Errors:

These errors arise due to three main reasons :

(i) Due to inherent shortcomings in the instrument,

(ii) Due to misuse of the instruments, and

(iii) Due to loading effects of instruments.

Inherent shortcomings of instruments: These errors are inherent in instruments because of their mechanical structure. They may be due to construction, calibration or operation of the instruments or measuring devices. Example: For example, if the spring (used for producing controlling torque) of a permanent magnet instrument has become weak, the instrument will always read high.

Misuse of Instrument: Too often, the errors caused in measurements are due to the fault of the operator than that of the instrument.

Examples which may be cited for this misuse of instrument may be failure to adjust the zero of instruments.

Loading effects: One of the most common errors committed by beginners, is the improper use of an instrument for measurement work. For example, a well calibrated voltmeter may give a misleading voltage reading when connected across a high resistance circuit.

(ii) Environmental Errors:

These errors are due to conditions external to the measuring device including conditions in the area surrounding the instrument. These may be effects of temperature pressure, humidity, dust, vibrations or of external magnetic or electrostatic fields.

(iii) Observational Errors:

(a) There are many sources of observational errors. As an example, the pointer of a voltmeter rests slightly above the surface of the scale. Thus, an error on account of **PARALLAX** will be incurred unless the line of vision of the observer is exactly above the pointer.

We can eliminate this error by having the pointer and the scale in the same plane.

(b) The sensing capabilities of individual observers affect the accuracy of measurement. Different experimenters may produce different results.

Modem electrical instruments have digital display of output which completely eliminates these errors.

3. RANDOM (RESIDUAL) ERRORS:

The happenings or disturbances about which we are unaware are lumped together and called "Random" or "Residual". Hence the errors caused by these happenings are called Random (or Residual) Errors.

Since these errors remain even after the systematic errors have been taken care of, we call these errors as Residual (Random) Errors.

Example: -Electronic noise in the circuit of an electrical instrument,
-Irregular changes in the heat loss rate from a solar collector due to changes in the wind.

4. LIMITING ERRORS (GUARANTEE ERRORS) :

In most instruments the accuracy is guaranteed to be within certain percentage of full-scale reading. The manufacturer has to specify the deviations from the nominal value of a particular quantity. The limits of these deviations from the specified value are defined as limiting errors or Guarantee errors. Thus the manufacturer has to specify the deviations from the nominal value of a particular quantity.

Example: the nominal magnitude of resistor is 10 Ω with a limiting error of 1, i.e. manufacturer guarantees that the value of resistance of the resistor lies between 9 Ω and 11 Ω.

5. RELATIVE (FRACTIONAL) LIMITING ERROR:

The relative (fractional) error is defined as the ratio of the error to the specified (nominal) magnitude of a quantity. Therefore,

In limiting errors, the specified quantity A_S is taken as the true quantity, and the quantity which has the maximum deviation from Aa is taken as the erroneous quantity. Thus, we have

$$\delta A = A_a - A_s$$

Relative limiting error, $E_r = \frac{A_a - A_s}{A_s}$

$$E_r = \frac{Actual\,Value - Nominal\,Value}{Nominal\,Value}$$

Source: A.K.Shawhney, "A Course in Electrical and Electronic Measurements and Instrumentation

1.6 Errors & Statistical Analysis

1.6.1 STATISTICAL TREATMENT OF DATA:

The experimental data is obtained in two forms of tests :

(i) Multisample test and (ii) Single-sample test.

Multisample test: In this test, repeated measurement of a given quantity are done using different test conditions such as employing different instruments, different ways of measurement and by employing different observers. Simply making measurements with the same equipment, procedure, technique and same observer do not provide multisample results.

Single-sample test: A single measurement (or succession of measurements) done under identical conditions excepting for time is known as single-sample test. In order to get the exact value of the quantity under measurement, tests should be done using as many different procedures, techniques and experimenters as practicable.

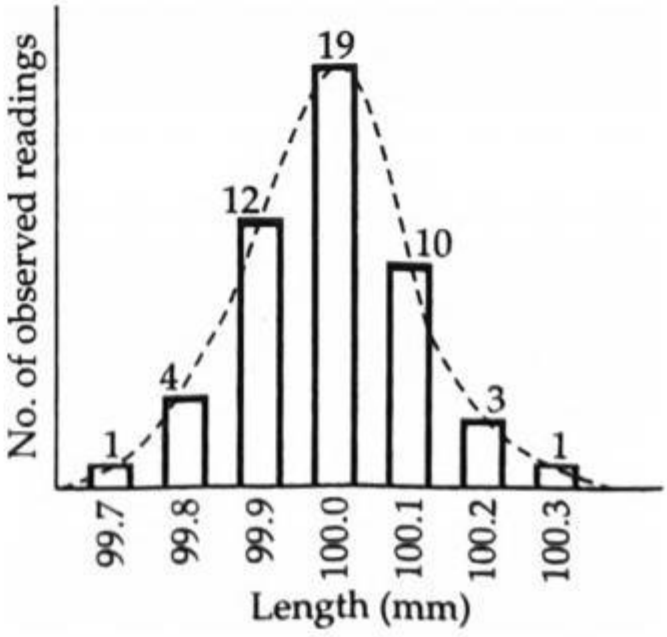
1.6.2 Histogram

When a number of multisample observations are taken experimentally there is a scatter of the data about some central value. One method presenting test results in the form of a Histogram. The technique is illustrated in Figure representing the data given in Table.This table shows a set of fifty readings of a length measurement.

Length(mm)	No.of Readings
99.7	1
99.8	4
99.9	12
100.0	19
100.1	10
100.2	3
100.3	1

Total No. of Readings = 50

The most probable or central value of length is 100 his histogram of Figure represents these data where the ordinate indicates the number of observed readings (frequency or occurrence) of a particular value. A histogram is also called a frequency distribution curve.



Histogram

1.6.3 Arithmetic Mean:

$$\overline{X} = \frac{x_1 + x_2 + x_3 + x_4 + ... + x_n}{n} = \frac{\sum x}{n} \quad ...(3.16)$$

where, $\overline{X}$ = arithmetic mean.

$x_1, x_2, ..., x_n$ = readings or variates or samples.

and n = number of readings.

1.6.4 Deviation:

Deviation is departure of the observed reading from the arithmetic mean of the group of readings. Let the deviation of reading x_1 be d_1 and that of reading x_2 be d_2, etc.

Then,

$$d_1 = x_1 - \overline{X}$$
$$d_2 = x_2 - \overline{X}$$
$$\cdots\cdots\cdots\cdots\cdots\cdots$$
$$d_n = x_n - \overline{X}$$
$$\overline{X} = \frac{\Sigma(x_n - d_n)}{n}$$

Algebraic sum of deviations

$$= d_1 + d_2 + d_3 + \ldots + d_n$$
$$= (x_1 - \overline{X}) + (x_2 - \overline{X}) + (x_3 - \overline{X}) + \ldots + (x_n - \overline{X})$$
$$= (x_1 + x_2 + x_3 + \ldots + x_n) - n\overline{X} = 0$$

as $x_1 + x_2 + x_3 + \ldots + x_n = n\overline{X}$

Therefore the algebraic sum of deviations is zero.

1.6.5 Average Deviation:

Average deviation is defined as the sum of the absolute values of deviations divided by the number of readings.

Average deviation may be expressed as,

$$\overline{D} = \frac{|-d_1| + |-d_2| + |-d_3| + \ldots + |-d_n|}{n} = \frac{\Sigma|d|}{n}$$

1.6.6 Standard Deviation (S.D.):

The Standard Deviation of an infinite number of data is defined as the square root of the sum of the individual deviations squared, divided by the number of readings.

Thus standard deviation is :

$$\text{S.D.} = \sigma = \sqrt{\frac{d_1^2 + d_2^2 + \ldots + d_n^2}{n}} = \sqrt{\frac{\Sigma d^2}{n}}$$

In practice, however, the number of observations is finite. When the number of observations is greater than 20, S.D. is denoted by symbol o while if the number of observations is less than 20, the symbol used is s. The Standard Deviation of a finite number of data is given by,

$$s = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \ldots + d_n^2}{n-1}} = \sqrt{\frac{\Sigma d^2}{n-1}}$$

1.6.7 Variance:

The variance is the mean square deviation, which is the same as S.D., except that square root is not extracted.

$$\text{Variance } V = (\text{Standard Deviation})^2$$
$$= (\text{S.D.})^2 = \sigma^2 = \frac{d_1^2 + d_2^2 + d_3^2 + \ldots + d_n^2}{n}$$
$$= \frac{\Sigma d^2}{n}$$

But when the number of observations is less than 20

$$\text{Variance } V = s^2 = \frac{\Sigma d^2}{n-1}$$

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1.7 uncertainty analysis

expression of uncertainty: accuracy and precision index, propagation of errors

Some numerical statements are exact: Mary has 3 brothers, and 2 + 2 = 4. However, all measurements have some degree of uncertainty that may come from a variety of sources. The process of evaluating the uncertainty associated with a measurement result is often called uncertainty analysis or sometimes error analysis.

The complete statement of a measured value should include an estimate of the level of confidence associated with the value.

Properly reporting an experimental result along with its uncertainty allows other people to make judgments about the quality of the experiment, and it facilitates meaningful comparisons with other similar values or a theoretical prediction.

When making a measurement, we generally assume that some exact or true value exists based on how we define what is being measured.

While we may never know this true value exactly, we attempt to find this ideal quantity to the best of our ability with the time and resources available. As we make measurements by different methods, or even when making multiple measurements using the same method, we may obtain slightly different results.

So how do we report our findings for our best estimate of this elusive true value? The most common way to show the range of values that we believe includes the true value is

measurement = (best estimate ± uncertainty) units

For example: We might say that the length of a certain stick measures 20 centimetres plus or minus 1 centimetre, at the 95 percent confidence level. This result could be written:

20 cm ±1 cm, at a level of confidence of 95%.

The statement says that we are 95 percent sure that the stick is between 19 centimetres and 21 centimetres long

how do you know that it is accurate, and how confident are you that this measurement represents the true value?

To help answer these questions, we first define the terms accuracy and precision:

Accuracy is the closeness of agreement between a measured value and a true or accepted value. Measurement error is the amount of inaccuracy.

Precision is a measure of how well a result can be determined (without reference to a theoretical or true value). It is the degree of consistency and agreement among independent measurements of the same quantity; also, the reliability or reproducibility of the result.

The accuracy and precision can be pictured as follows:

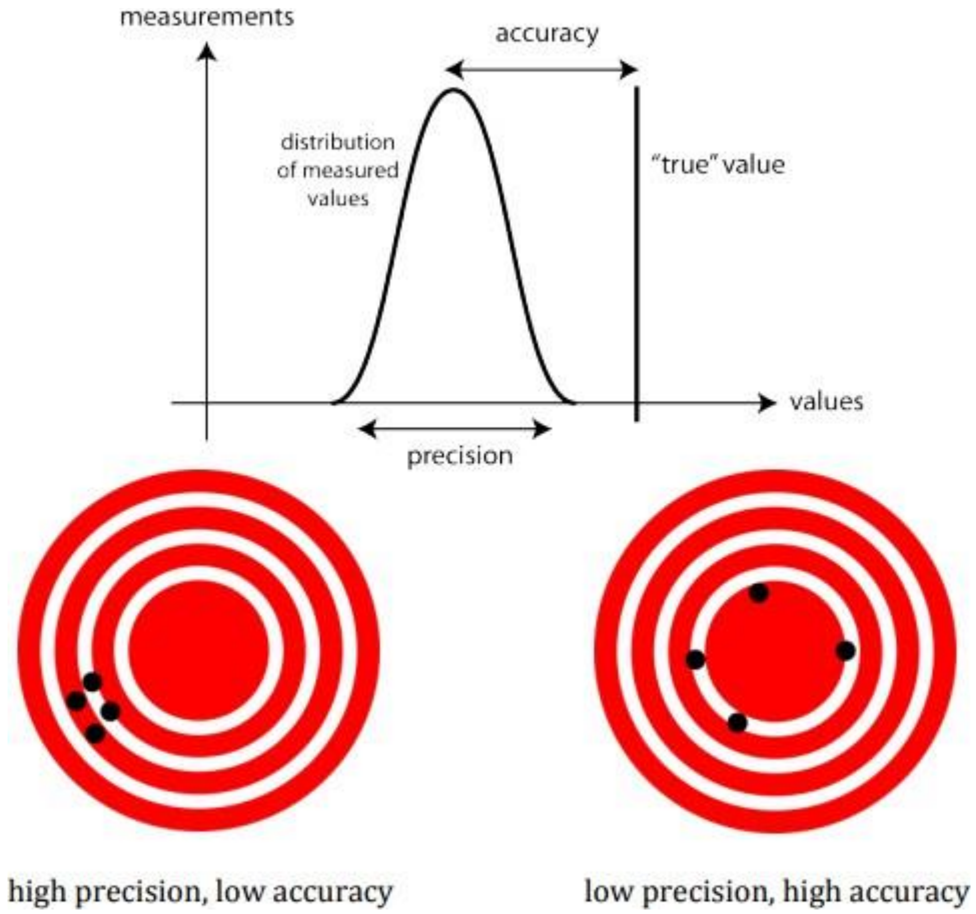

Figure 1.7.1 Accuracy vs Precision

The uncertainty estimate associated with a measurement should account for both the accuracy and precision of the measurement. Precision indicates the quality of the measurement, without any guarantee that the measurement is "correct." Accuracy, on the other hand, assumes that there is an ideal "true" value, and expresses how far your answer is from that "correct" answer. These concepts are directly related to random and systematic measurement uncertainties.

Precision is often reported quantitatively by using relative or fractional uncertainty.

$$Relative\ Uncertainty = \left|\frac{Uncertainty}{Measured\ quantity}\right|$$

For example, m = 75.5 ± 0.5 g has a fractional uncertainty of: $\frac{0.5g}{75.5g} = 0.006 = 0.7\%$

Accuracy is often reported quantitatively by using relative error:

$$Relative\ Error = \frac{Measured\ Value - Expected\ Value}{Expected\ Value}$$

If the expected value form is 80.0 g, then the relative error is =

$$\frac{75.5 - 80.0}{80.0} = -0.056 = -5.6\%$$

Types of Uncertainty Measurement:

Uncertainties may be classified as either random or systematic, depending on how the measurement was obtained (an instrument could cause a random uncertainty in one situation and a systematic uncertainty in another).

Random uncertainties are statistical fluctuations (in either direction) in the measured data. These uncertainties may have their origin in the measuring device, or in the fundamental physics underlying the experiment. The random uncertainties may be masked by the precision or accuracy of the measurement device. Random uncertainties can be evaluated through statistical analysis and can be reduced by averaging over a large number of observations (see "standard error" later in this document).

Systematic uncertainties are reproducible inaccuracies that are consistently in the "same direction," and could be caused by an artifact in the measuring instrument, or a flaw in the experimental design (because of these possibilities, it is not uncommon to see the term "systematic error"). These uncertainties may be difficult to detect and cannot be analyzed statistically. If a systematic uncertainty or error is identified when calibrating against a standard, applying a correction or correction factor to compensate for the effect can reduce the bias. Unlike random uncertainties, systematic uncertainties cannot be detected or reduced by increasing the number of observations.

Estimating Uncertainty in Repeated Measurements:

If you repeat the measurement several times and examine the variation among the measured values, you can get a better idea of the uncertainty in the period. For example, here are the results of 5 measurements, in seconds: 0.46, 0.44, 0.45, 0.44, 0.41. For this situation, the best estimate of the period is the **average, or mean**:

$$Average(Mean) = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

Whenever possible, repeat a measurement several times and average the results. This average is generally the best estimate of the "true" value (unless the data set is skewed by one or more outliers which should be examined to determine if they are bad data points that should be omitted from the average or valid measurements that require further investigation). Generally, the more repetitions you make of a measurement, the better this estimate will be, but be careful to avoid wasting time taking more measurements than is necessary for the precision required.

One way to express the variation among the measurements is to use the ***average deviation***. This statistic tells us on average (with 50% confidence) how much the individual measurements vary from the mean.

$$Average\ Deviation, \bar{d} = \frac{|x_1 - \bar{x}| + |x_2 - \bar{x}| + \cdots + |x_N - \bar{x}|}{N}$$

The average deviation would seem to be a sufficient measure of uncertainty; however, it is important to understand the distribution of measurements.

Standard Deviation:

To calculate the standard deviation for a sample of N measurements:

1. Sum all the measurements and divide by N to get the average, or mean.
2. Subtract this average from each of the N measurements to obtain N "deviations."
3. Square each of the N deviations and add them together.
4. Divide this result by (N–1) and take the square root.

To convert this into a formula, let the N measurements be called x_1, x_2, …, x_N. Let the average of the N values be called x . Then each deviation is given by

$$\delta x_i = x_i - \bar{x} \qquad for\ i = 1,2, \ldots N$$

The standard deviation is then:

$$S = \sqrt{\frac{(\delta x_1{}^2 + \delta x_2{}^2 + \cdots + \delta x_N{}^2)}{(N-1)}} = \sqrt{\frac{\sum \delta x_i{}^2}{(N-1)}}$$

Standard Deviation of the Mean (Standard Error) When reporting the average value of N measurements, the uncertainty associated with this average value is the standard deviation of the mean, often called the Standard Error (SE),

Standard Deviation of the Mean, or Standard Error (SE),

$$\sigma_{\bar{x}} = \frac{s}{\sqrt{N}}$$

The standard error is smaller than the standard deviation by a factor of $1/\sqrt{N}$. This reflects the fact that we expect the uncertainty of the average value to get smaller when we use a larger number of measurements.

Significant Figures:

The number of significant figures in a value can be defined as all the digits between and including the first non-zero digit from the left, through the last digit. For instance, 0.44 has two significant figures, and the number 66.770 has 5 significant figures. Zeroes are significant except when used to locate the decimal point, as in the number 0.00030, which has 2 significant figures. Zeroes may or may not be significant for numbers like 1200, where it is not clear whether two, three, or four significant figures are indicated.

Propagation of Errors:

- The analysis of uncertainties (errors) in measurements and calculations is essential in the physics laboratory.
- For example, suppose you measure the length of a long rod by making three measurement $x = x_{best} \pm \Delta x$, $y = y_{best} \pm \Delta y$, and $z = z_{best} \pm \Delta z$.
- Each of these measurements has its own uncertainty Δx, Δy, and Δz respectively. What is the uncertainty in the length of the rod $L = x + y + z$? When we add the measurements do the uncertainties Δx, Δy, Δz cancel, add, or remain the same?

- Likewise, suppose we measure the dimensions $b = b_{best} \pm \Delta b$, $h = h_{best} \pm \Delta h$, and $w = w_{best} \pm \Delta w$ of a block. Again, each of these measurements has its own uncertainty Δb, Δh, and Δw respectively. What is the uncertainty in the volume of the block V = bhw? Do the uncertainties add, cancel, or remain the same when we calculate the volume? In order for us to determine what happens to the uncertainty (error) in the length of the rod or volume of the block we must analyze how the error (uncertainty) propagates when we do the calculation. In error analysis we refer to this as ***error propagation***.
- There is an error propagation formula that is used for calculating uncertainties when adding or subtracting measurements with uncertainties and a different error propagation formula for calculating uncertainties when multiplying or dividing measurements with uncertainties. Let's first look at the formula for adding or subtracting measurements with uncertainties.
- **Adding or Subtracting Measurements with Uncertainties**: Suppose you make two measurements,

$$x = x_{best} \pm \Delta x$$

$$y = y_{best} \pm \Delta y$$

What is the uncertainty in the quantity q = x + y or q = x – y? To obtain the uncertainty we will find the lowest and highest probable value of q = x + y. Note that we would like to state q in the standard form of $q = q_{best} \pm \Delta q$ where

$$q_{best} = x_{best} + y_{best}$$

(highest probable value of q = x + y):

$$(x_{best} + \Delta x) + (y_{best} + \Delta y) = (x_{best} + y_{best}) + (\Delta x + \Delta y) = q_{best} + \Delta q$$

(lowest probable value of q = x + y):

$$(x_{best} - \Delta x) + (y_{best} - \Delta y) = (x_{best} + y_{best}) + (\Delta x + \Delta y) = q_{best} - \Delta q$$

Thus, we that

$$\Delta q = \Delta x + \Delta y$$

is the uncertainty in q = x + y

Precision Index:

The precision index describes the spread or dispersion of repeated result about a central value.

(a) 105

(b) 105.0

(c) 0.00105×10^5

(a) and (c) - have three significant figure.

(b) - has four significant figure So (b) has higher precision

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1.8 Calibration – Primary and Secondary Standards

1.8.1 Static Calibration:

All the static performance characteristics are obtained in one form or another by a process called static calibration. The calibration of all instruments is important since it affords the opportunity to check the instrument against a known standard and subsequently to find errors and accuracy.

Calibration procedures involve a comparison of the particular instrument with either (1) a primary standard, (2) a secondary standard with a higher accuracy than the instruments be calibrated, or (3) an instrument of known accuracy.

Actually, all working instruments, i.e., those instruments which are actually used for measurement work must be calibrated against some reference instruments which have a higher accuracy. Thus, reference instruments in turn must be calibrated against instrument of still higher grade of accuracy, or against primary standard, or against other standards of known accuracy. It is essential that any measurement made must ultimately be traceable to the relevant primary standards.

1.8.2 The need for calibration:

Measurement is vital in science, industry and commerce. Measurement is also performed extensively in our daily life. The following are some examples:

- Measurements for health care, such as measuring body temperature with a clinical thermometer, checking blood pressure and many other tests;

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- Checking the time of day;
- Buying cloth for dresses;
- Purchase of vegetables and other groceries;
- Billing of power consumption through an energy meter.

Accuracy and reliability of all such measurements would be doubtful if the instruments used were not calibrated. Calibration ensures that a measuring instrument displays an accurate and reliable value of the quantity being measured. Thus, calibration is an essential activity in any measurement process.

1.8.3. What is calibration?

According to the International Organization for Standardization publication entitled International Vocabulary of Basic and General Terms in Metrology (published in 1993 and known as VIM), calibration is the set of operations that establish, under specified conditions, the relationship between values indicated by a measuring instrument, a measuring system or values represented by a material measure, and the corresponding known values of a measurand (the parameter that is being measured; see also chapter 9 below for a fuller explanation of the term "measurand"). Understanding of calibration is not complete without understanding traceability. In the above definition, the known values of the measurand refer to a standard. This standard must have a relationship vis-à-vis the calibration.

Traceability: *The concept of establishing valid calibration of a measuring standard or instrument by step-by-step comparison with better standards up to an accepted national or international standard. Essentially, calibration is a comparison with a higher standard that can be traced to a national or international standard or an acceptable alternative.*

1.8.4 Periodicity of calibration:

Periodicity of calibration generally would be finalized based on recorded investigation. This means that calibration results of an instrument must be monitored over time and, depending on the drift it exhibits, the time period between recalibration can be decided. However, this is possible only after a few recalibrations. How should the initial recalibration interval be fixed? The initial decision to determine the calibration interval is based on the following factors:

- Recommendation of the instrument manufacturer;
- How frequently and severely the instrument is expected to be used;
- The influence of the environment;
- Maximum allowable variation of the measurand;
- The uncertainty of measurement required.

Such a decision should, however, be made by a person with experience of measurement and who is knowledgeable about calibration of the instrument. This experience and knowledge would help in estimating the length of time an instrument is likely to remain within tolerance after calibration. However, clearly there cannot be one universal method of determining the calibration periodicity for all types of measuring instruments.

1.8.5 Primary Standards:

- Primary standards are absolute standards of such high accuracy that they can be used as the ultimate reference standards.
- These standards are maintained by national standards laboratories in different parts of the world. The primary standards, which represent the fundamental units and some of the derived electrical and mechanical units, are independently calibrated by absolute measurements at each of the national laboratories.
- The results of these measurements are compared against each other, leading to a world average figure for the primary standards.
- Primary standards are not available for use outside the national laboratories. One of the main functions of the primary standards is the verifications and calibration of secondary standards.
- The primary standards are few in number. They must have the highest possible accuracy. Also, these standards must have the highest stability, i.e., their values should vary as small as possible over long periods of time even if there are environmental and other changes.
- In the recent past, the techniques of establishing primary standards have been drastically refined so that accuracy attainable has become of a very high level.

1.8.6 Secondary Standards:

- The secondary standards are the basic reference standards used in industrial measurement laboratories.
- The responsibility of maintenance and calibration of these standards lies with the particular industry involved.
- These standards are checked locally against reference standards available in the area. Secondary standards are normally sent periodically to the national standards laboratories for calibration and comparison against primary standards.
- The secondary standards are sent back to the industry by the national laboratories with a certification as regards their measured values in terms of primary standards.

Example:

Two type of transduction occurs in the Bourdon's tube. First, the pressure is converted into a displacement and then it is converted into the voltage by the help of the L.V.D.T. The Bourdon's Tube is the primary transducer, and the L.V.D.T is called the secondary transducer.

1.8.7 Applications of Sensor Calibration:

1. The calibration process is used to increase the performance and functionality of the system.
2. It helps in reducing errors in the system. A calibrated sensor provides accurate results and can be used as a reference reading for comparison.
3. With the increase in the embedded technology and low size of sensors, many sensors are integrated over a single chip. Undetected errors in one sensor can cause the whole system to degrade. It is important to calibrate the sensor to get the accurate performance of the automated systems.

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